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A TRANSDUCTOR TYPE FIELD RIPPLE DETECTOR FOR SYNCHRONOUS GENERATORS

H. M. McCONNELL

MAGNETIC AMPLIFIERS - TECHNICAL REPORT NO. 18

Work performed under Office of Naval Research Contracts
N7 ONR 30306 and 30308 - PROJECTS NO. 975-272 and 275

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SYNOPSIS

Magnetic amplifier techniques are used to synthesize a device which acts as a current transformer, to detect the alternating component of a current in the presence of large amounts of superposed direct current. Conventional current transformers for this service must be prohibitively large in order to avoid saturation of the magnetic circuit. The present device is small, light in weight, and has accuracy suitable for instrumentation.

The particular application for which the device was designed is the detection and measurement of double-frequency ripples in the field current of a synchronous generator. This ripple current is proportional to the negative-sequence component of stator current. Large negative sequence currents are objectionable, since corresponding induced currents in the rotor structure cause destructive heating. The device described in this report forms the detecting element for a protection scheme. It replaces more elaborate negative-sequence segregating networks.

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June, 1954

A TRANSDUCTOR TYPE FIELD RIPPLE DETECTOR FOR SYNCHRONOUS GENERATORS

Introduction

It has been recognized that negative sequence stator currents in synchronous generators, if allowed to persist, may cause dangerous heating of the rotor structure due to induced currents. The problem of protecting synchronous generator against rotor heating from this cause has stimulated an active discussion among those responsible for relay application.

The present method of detecting negative sequence stator current is to employ well known sequence filtering networks fed by current transformers. The output of the network is used to operate a relay which actuates protective equipment if the permissible "I^2T", or integrated square of negative sequence current, is exceeded. A group of recent papers, references 1 to 5 inclusive, summarize the present state of development in this matter.

At the time of presentation of these papers, it was mentioned in oral discussion that a method of detection of negative sequence currents based on the induced a-c component of field current would be desirable. It is well known that a proportionality exists between these quantities. However, a conventional current transformer is not satisfactory to detect the a-c component of field current, due to the presence of the steady d-c component which saturates the transformer.

This paper presents a circuit for the measurement of the a-c component of a current which has a considerable d-c level, with particular application to the field ripple problem at hand. The circuit consists of current transformer with an additional compensating winding supplied by a current transductor, whose function is to cancel the d-c ampere turns. The circuit is shown in Figure 1. The cores are made in gapless (toroidal) form, of a material having essentially a rectangular hysteresis loop.

Design Objectives

The objectives in designing the circuit are to achieve (a) a useful output current I_o into the burden Z_o; (b) faithful response to sudden changes in either the d-c or a-c components of the current I_f; (c) acceptable linearity between I_o and the a-c component of I_f. An approximate analysis of the circuit indicates the way in which the various circuit components must be chosen in order to meet these objectives.

Analysis

The transductor will be idealized by stating that the instantaneous current I_1 (see Figure 1) is the image of the instantaneous current I_f. Reasonably close agreement between this idealization and actual performance is obtained if the resistance drop in the a-c windings of the transductor, $2 r_1 i_1$, is small

compared with the maximum applied voltage, and the capacitor C offers low impedance to the a-c component of I_1. A detailed analysis of the transductor operation is beyond the scope of this paper; in fact, the performance of the series-connected magnetic amplifier with high impedance control circuit is not well understood due to unexplained core behavior. It is sufficient to note here that the compensating turns of the current transformer may be adjusted to account for linear departures of the transductor performance from the ideal. Thus,

$$I_1 = \frac{I_f}{N_1} k_1 \tag{1}$$

where k_1 is the proportionality factor which accounts for the current ratio error of the transductor.

For perfect compensation of the current transformer,

$$N_2 I_{1(dc)} = I_{f(dc)} \quad ; \tag{2}$$

therefore

$$N_2 = \frac{N_1}{k_1} \, . \tag{3}$$

The current transformer is idealized by neglecting its magnetizing current. Then, the ampere-turn relationship states that

$$\bar{I}_{f(ac)} = N_o \bar{I}_o + N_2 \bar{I}_{2(ac)} \tag{4}$$

The common flux Φ of windings N_o and N_2 require that

$$\bar{I}_o \bar{Z}_o = j\omega N_o \bar{\Phi} \tag{5}$$

$$\bar{I}_{2(ac)} (r_2 + j\omega L) = j\omega N_2 \bar{\Phi} \tag{6}$$

The reactance offered by C at the ripple frequency $\omega/2\pi$ is not included in equation (6) because the conducting arms of the rectifier bridge effectively short-circuit C to this component of current.

Combining equations (4), (5), and (6) yields the complex ratio of transformation

$$\frac{\bar{I}_o}{\bar{I}_{f(ac)}} = \frac{1}{N_o \left\{ 1 + \left(\frac{N_2}{N_o} \right)^2 \left(\frac{\bar{Z}_o}{r_2 + j\omega L} \right) \right\}} \tag{7}$$

The rapidity with which the bias current $I_{2(dc)}$ is able to adjust to transients in the d-c level of I_f will have an effect upon the current transformer behavior. During transient intervals both the d-c and a-c components of field current change suddenly. The current transformer can by itself reproduce such symmetrical currents in its output winding for a short time only; this time is dictated by the rate at which the average flux level of the current transformer core increases, which is in turn dictated by the burden.

It will be assumed here that the current transformer is unable to reproduce asymmetrical currents at all unless perfect compensation in the bias winding exists. Then a suitable transient response of the bias current I_2 will be defined as follows: the bias current should reach a level such that compensation is restored within an interval which is short in comparison with the short circuit transient time constant (T_d') of the generator. Taking 20 cycles to be a representative value of T_d', then the bias current should be able to reach the level for compensation in about 4 cycles at fundamental frequency.

Transients in the bias circuit will be calculated under assumptions that (a) the transductor delivers a direct current I_1 proportional to the d-c component of I_f; (b) the current transformer is saturated. Then, the bias winding (N_2) may be treated as a resistance, and the circuit L, r_2, C may be considered to receive a prescribed current. Rapid response with a minimum tendency to overshoot in a circuit of this type is achieved if the damping is somewhat less than the critical value. Accordingly, a damping ratio of 0.7 will be assumed. Previous discussion of response time has indicated that about (1/15) second may be allowed between initiation of a sudden change in I_1 and a corresponding response of I_2. As shown in any treatment of second-order systems of this type, the following relationships are established:

$$\left\{ \begin{aligned} &\frac{r_2 C}{2\sqrt{LC}} \cong 0.7 \\ &\frac{1}{\sqrt{LC}} \cdot \frac{1}{15} \cong 2.5 \end{aligned} \right. \tag{8}$$

or

$$\left\{ \begin{aligned} &\sqrt{LC} \cong 0.0267 \text{ sec} \\ &r_2 C \cong 0.0373 \text{ sec} \end{aligned} \right. \tag{9}$$

Whether the conditions of equations (9) may be realized depends on whether the filter circuit Q prescribed by these equations is practical. It is found that at the ripple frequency of 120 cycles the ratio ($\omega L / r_2$) dictated by (9) is about 14, which is readily obtained with commercial components.

Let it be required to design a field ripple detector for a generator in which, during transients, the d.c. component of field current may reach 400 amperes. The initial value of a.c. component of field current under such circumstances will be less than 400 amperes peak, by an amount equal to the initial field current. However, let it be assumed for purposes of design that the peak a.c. component will be 400 amperes; the detector should be designed for an a.c. level of 283 amperes

r.m.s. Let a burden of 10 volt-amperes at 1000 ohms be required at this a.c. level. These preliminary considerations fix the current transformer output at 100 m.a. r.m.s. and the current transformer output winding can have no more than 2830 turns. The current transformer core must be capable of at least (100/2830) volts per turn at 120 cycles.

Equation (7), together with the value of Q=14 dictated by equations (9), allows the determination of N_o and N_2 versus the parameter (N_2/N_o) for a given value of the second parameter r_2. If r_2 is assumed to take a certain value, then N_o and N_2 may be found such that the wire sizes, available winding spaces, and practically available choke fit the assumed value of r_2. Several trials of this nature indicate the combination best suited to the particular application considered. It is found that in the present example N_2 should be about 5000 and N_o should be about 2200 if it is assumed that r_2 is 500 ohms. The corresponding value of L is 9.30 henries. The rated value of the compensating current I_2 becomes 80 m.a. and the rectifier must withstand 40 volts d.c. The capacitor should be about 75 microfarads, although the exact value is not critical (equation 8).

Experimental Work

A model of the circuit has been constructed and tested. The three cores were made of 0.004" "Orthonol" tape. The dimensions (in inches) are:

	Core			Box		
Core	ID	OD	H	ID	OD	H
α, β	1.25	1.75	0.50	1.18	1.82	0.61
γ	1.50	2.00	1.00	1.40	2.10	1.11

Other constants of the circuit are:

N_1	5000 turns #32
N_2	5000 turns #32
N_o	2200 turns #32
$2r_1$	304 ohms (20°C)
r_2	501 ohms (20°C)
L	10.5 henry (nominal)
C	50 Mfd 50 volts electrolytic

A factor k_1 was introduced in equation (1) to account for the fact that the ampere-turn ratio of the transductor is slightly less than the ideal of unity. It will be noted that both N_1 and N_2 are 5000 turns in the model. The factor k_1 is introduced in an equivalent way in the model by placing more exciting turns upon the transductor cores than upon the current transformer core, turns being added until maximum output current is reached at rated dc and ac excitation levels. It was found that 72 turns on the transductor cores and 69 turns on the current transformer core achieved this result. Thus $k_1 = 69/72 = 0.958$. Rated d-c current becomes 5.80 amperes and rated a-c ripple current becomes 4.08 amperes rms. (The example design began by assuming 400 amperes in a single conductor to be the excitation level. In order to test the model on available machines, the nominal 70-turn exciting windings were installed. In a single conductor application it would be most convenient to add extra turns to the current transformer compensating winding, in about 1/2 per cent taps, in order to "tune" for best compensation).

The steady-state response of the unit at 60 cycles is given in Figure 2. Transient response, in the situation for which the unit was designed, is shown in the oscillograms of Figures 3 and 4. (It will be noted that the d-c component of generator field current in Figure 4 rises to a value considerably greater than the designed level, resulting in some distortion of the output current wave form and a reduction in its r.m.s. value).

Conclusions

The device presented in this paper is shown to be a small, inexpensive, static apparatus for the measurement of the a-c component of field current in a synchronous generator, both in the transient and steady states. It has sufficient output to operate a relay or meter. Its design is simple and its components are readily obtained.

Probably the most serious obstacle to the application of this device to generator protection is the determination, without dangerous tests, of the amount of a-c ripple in field current per unit of generator negative-sequence current. Accurate calculations are possible in the case of salient-pole generators. However, the presence of solid iron in the rotor forging of a turbo-generator upsets any formal calculation for those machines.

Acknowledgements

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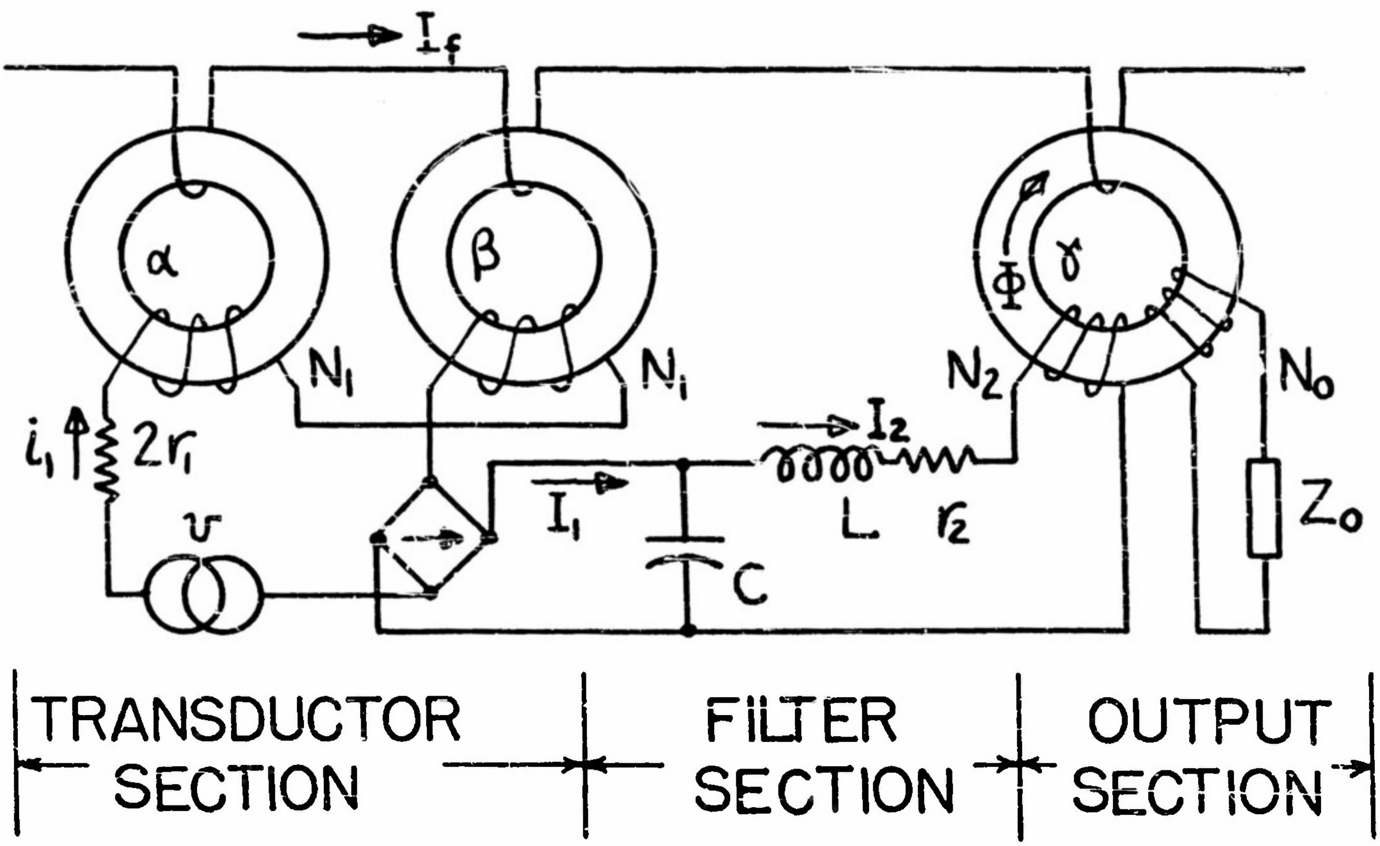

Figure 1. Circuit diagram of the transductor type field ripple detector.

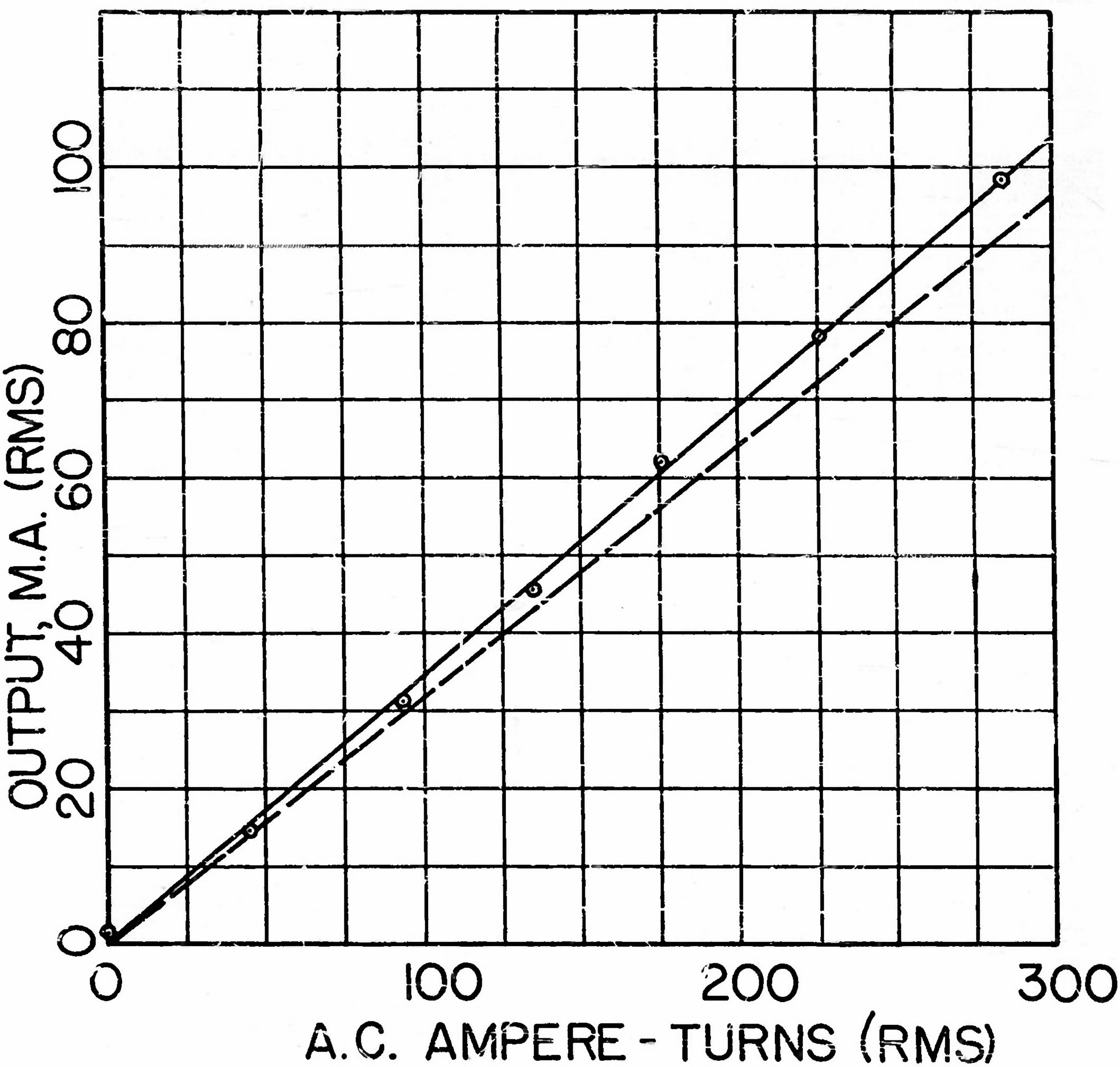

Figure 2. Steady-state output characteristic at 60 cycles, with 400 ampere-turns d.c., and 585 ohms resistive load.

Dashed curve: Calculated by equation (7)
Solid curve: Measured.

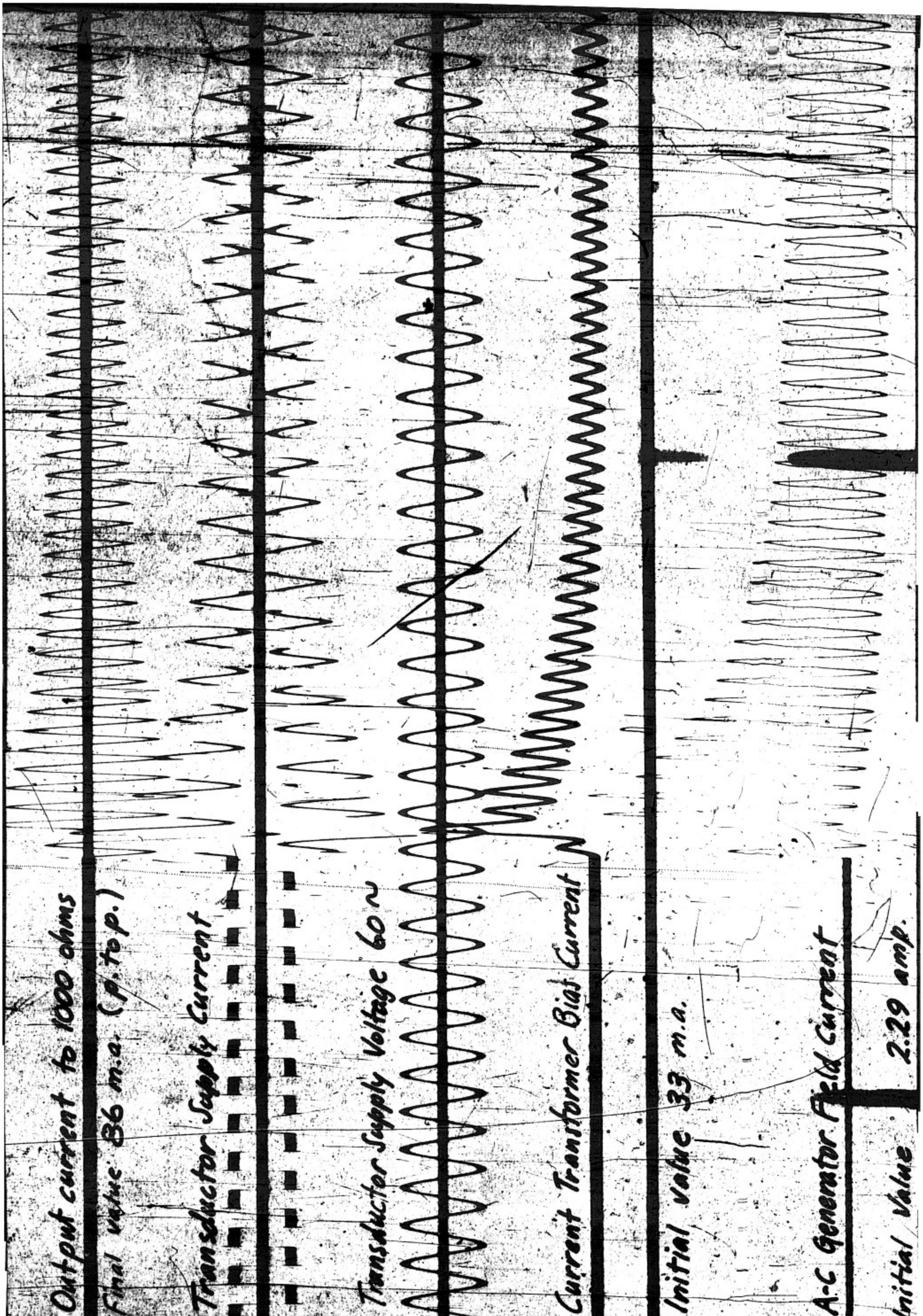
Output current to 1000 ohms
Final value 36 m.a. (p. to p.)
Transductor Supply Current
Transductor Supply Voltage 60~
Current Transformer Bias Current
Initial value 33 m.a.
A-C Generator Field Current
Initial Value 2.29 amp.

Figure 3

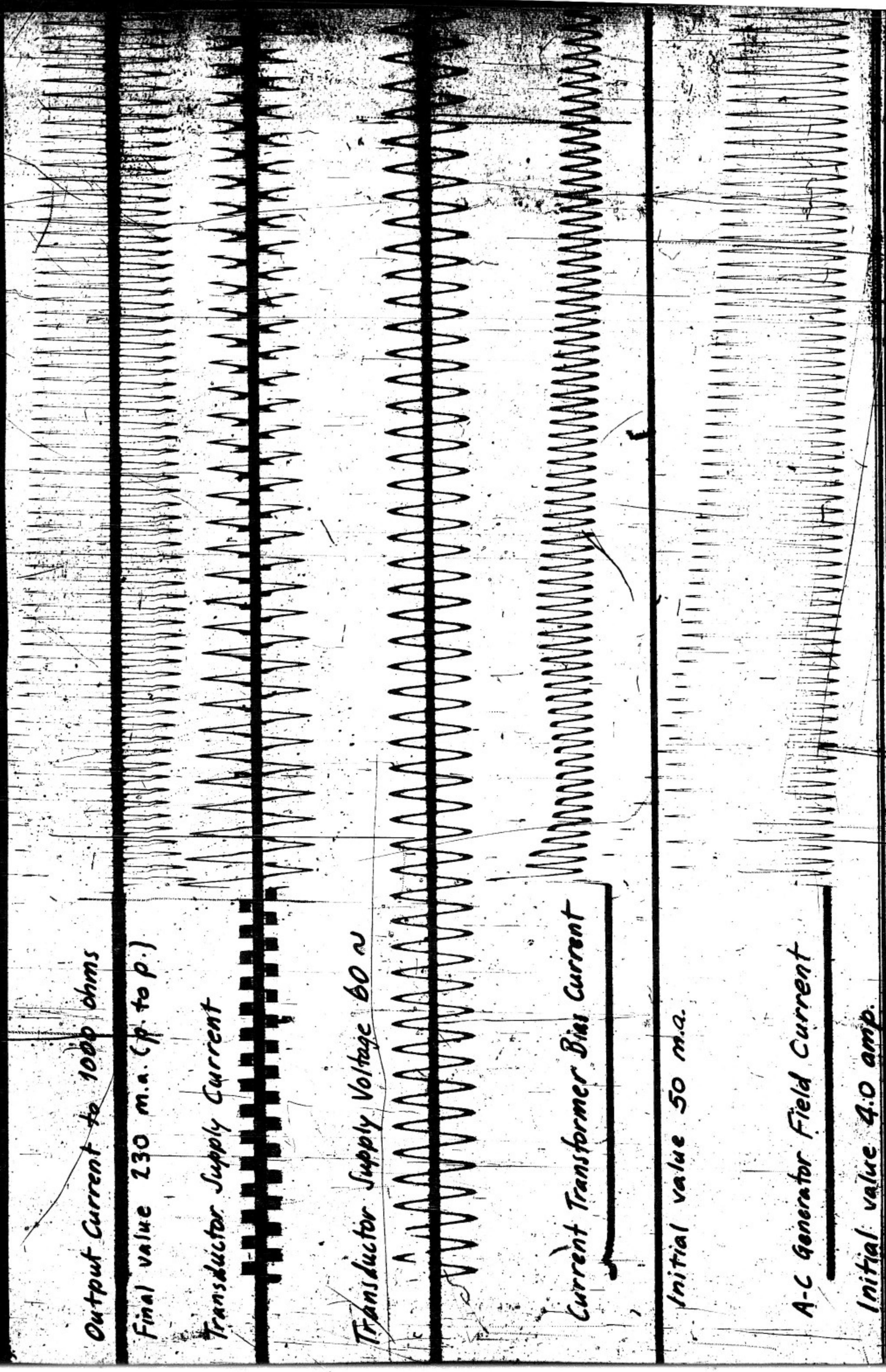
Output Current to 1000 ohms
Final value 230 m.a. (p. to p.)
Transductor Supply Current
Transductor Supply Voltage 60 ~
Current Transformer Bias Current
Initial value 50 m.a.
A-C Generator Field Current
Initial value 4.0 amp.

Figure 4